Evaluating Fit by Using Animated Body Scan Avatars and Digital Coveralls

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Abstract

Digital garment simulations can be very useful for technical design teams when evaluating the fit of the functional or protective garments, especially when 3D body scanning technology is unable to fully capture certain poses. In this study, we tested a method of creating animated coverall simulations and using the obj files of three poses, i.e., A-pose, reaching front, and stepping front, for objective and subjective fit analyses. We used 29 body scans that were rigged in Mixamo to analyze ease amounts of digitally stitched coveralls in each pose. Pattern outlines were visible in the digital coveralls Circumferences, cross sections, volumes, as well as crotch heights, were measured from the obj files of the clothed and minimally clothed digital bodies. Results showed that our method was effective in creating realistic wrinkles/folds that indicate tightness. There were significant differences in the overall ease across the three poses. A-pose yielded the highest overall ease followed by reaching front and stepping front. Crotch ease was significantly the lowest in the stepping front pose. Animations were found to be signaling additional fit clues.

Keywords: Protective clothing, coverall, simulation, dynamic fit, cross-sections

1. Introduction

Protective coveralls are whole-body garments, which are designed to prevent the wearer from viruses or harmful chemicals such as pesticides. Coveralls are unisex garments, typically with a hood and zippered front, and rectangular in shape. They are made from non-woven fabrics and are expected to fit a wide range of body types as well as provide comfort, mobility, and protection to the wearer [1]. If coveralls are too tight, they might tear when the wearer reaches or steps up. If coveralls have excess fabric, they may get caught in machinery [2]. Traditionally, garment fit is established during product development for static poses by adding pre-determined ease amounts to two-dimensional (2D) patterns. However, static ease amounts needed at various body locations change greatly when wearers perform work-related tasks [2]. Therefore, in addition to examining garment fit in static poses, garment-body relationships must be analyzed in dynamic poses to ensure that ease amounts accommodate the required range of motions without garment interference and resistance [3,4].

Three-dimensional (3D) body scanning technology allows for capturing body measurements and shapes quickly and reliably [5]. Although using 3D body scans in active poses can help with analyzing garment fit, some 3D body scanners cannot capture the surfaces that exceed the scan envelope. Additionally, performing physical trials for different body shapes and sizes may not be feasible in terms of cost and time. Therefore, it is important to understand the capabilities of simulations and how they can be used for fit testing of a protective garment design. For the present study, digital and animated coverall prototypes were created to imitate an existing coverall design and conduct objective and subjective fit analyses. Scan visuals were used as a baseline to ensure both sets are visually close in terms of proportions and drape.

2. Literature Review

2.1. Fit Analysis of Protective Clothing

One of the main aspects of clothing comfort apart from social, physiological, and psychological factors is the physical factor. The physical fit of a garment is determined by numerous factors including ease allowance, line, grain, balance, and set [7]. Sufficient ease allows the wearer to move without restriction. To ensure wearers can perform their best, protective clothing should not restrict motion by being too tight or too loose. Comfort depends on the interaction between the garments and the body, which in turn depends on the body shape and size, personal preferences, activities to be performed, fabric

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properties, and pattern shapes [2, 8]. In functional garments, restriction to movement is often eliminated by making the garment loose, leaving unattached areas that separate, leaving open areas or slits, adding elastic panels, adding pleats or gathers, and so on [8]. Past studies incorporated elastic panels [9,10], however, elastic panels might result in exposing the wearer to dangerous environments when stretched. Another approach to enhancing garment fit is using kinetic garment construction to create more flexible garments through bias cuts [11].

Many researchers have studied the fit, comfort, and durability of protective coveralls from different perspectives. For example, a mobility analysis test was developed and applied for investigating the mobility issues of disposable coveralls [12]; alternative coverall designs of added crotch ease were designed and the effects of adding ease in specific areas and subjective perceptions of fit comfort, and mobility were studied [10,13]; and restrictions in mobility under varying working positions were investigated [14]. In another study, personal protective coveralls were re-designed, a sizing system was developed, and coveralls were tested by using 3D body scan technology [9, 15].

As the wearer moves, the body shape changes, and consequently ease amounts at various body locations change [3]. Improper fit of protective coveralls such as excess crotch length may restrict movement, hinder performance, and cause the garment to tear, thereby, exposing the wearer to dangerous environments [1]. Restriction to movement might also cause the worker to not wear protective gear [13]. Previously, the fit was evaluated by measuring the range of motion, seam analysis, visual analysis, and wearers' subjective preferences [13]. Male wearers were found to be more satisfied with the unisex medical uniforms as compared to women and wearers reported the highest dissatisfaction with the fit of pants and then shirts [16].

2.2. 3D Body Scanning for Fit Analysis

Linear body measurements do not represent the body completely. 3D body scanning can allow quick extraction of both body measurements and body shapes [6]. The positions to analyze the garment fit can be chosen based on the tasks performed while wearing the protective gear. The ability to analyze fit in a particular position, zoom and rotate a specific area when using body scans to perform fit analyses gives an advantage [17]. Additionally, individuals' perceptions of the threshold of the right fit of the garment can be different for each location. Garment fit perceptions may be influenced based on personal preferences, and even change from time to time [18]. This makes it essential to complement subjective data obtained through participant fit feedback and expert visual fit analysis with objective fit measurements which has been made possible through 3D scans and simulations [19].

Previously, slashes in different orientations have been used to quantify stress in terms of tears with changes in a position [12]. With advancements in technology, researchers have used body scan data to perform statistical analysis to evaluate garment fit. The ease measurements at locations such as crotch, shoulder, armpits, etc. were determined in various sitting and bending postures [20]. Three different coverall patterns were developed with ease measurements applied at different locations as well as amounts and tested in six body postures Results indicated that the ease must be applied at the waist and hip for coveralls [20]. 3D body scans have been used to analyze clothing protection, ease of movement, and thermal comfort. In a previous study, the impact of fabric properties, clothing size, garment design, and body parts on the interaction between the clothing and the human body was studied to improve the design of thermal protective clothing [21]. The air gap and distribution were calculated by superimposing the unclothed and clothed body, extracting horizontal slices, and calculating the minimum, maximum, and average distance between the contour lines [21]. Results of the study indicated that air gaps had an uneven distribution with larger gaps in the legs and abdomen as compared to lesser air gaps in the chest, pelvis, and arms [21]. Additionally, the air gap increased with an increase in garment size and stiffness of fabric [21]. As another approach, the cross-sectional area can be calculated to analyze the garment fit [22, 23]. For example, to analyze the fit of pants, researchers divided the leg into five cross sections from waist to ankle and calculated the ease measurement as the difference between the two circumferences, area, and volume measurements [24, 25]. Performing such analysis at key locations such as the chest and waist was proved to be useful for garment fit analysis [22]. In another study, the 3D scan of the clothed participants was visually analyzed by expert judges at 13 locations for ease, line, balance, and set [17].

Body scanning along with 3D simulation software has been used to study the interaction between the body and garment. Motion capture technology was used animate the avatars and the garment deformation was calculated [26]. Despite all of the aforementioned benefits in objective fit analysis, 3D body scanners have several limitations. Scanners require space, are expensive, and can only scan visible areas. Therefore, the armhole and crotch areas are difficult to capture, and dynamic poses often

lead to holes in the scan. Additionally, several factors impact the scanning process. For instance, the lighting conditions, fit of clothing worn during scanning, body sway, and so on can lead to imprecise measurements. Therefore, the use of simulations can provide cheaper, quick support for technical designers, especially the ones with less experience when analyzing garments. The errors introduced by manual overlapping of scans can be eliminated when using virtual garment simulations to extract cross sections and study the relationship between the body and the garment.

2.3. Physical Garment Fit vs Virtual fit: Animated Simulations

People have different body shapes and sizes based on which garments fit very differently [27, 28]. Performing physical trials for multiple bodies may not be feasible in terms of cost and time [29]. Virtual try-on can enable the quick evaluation of garment fit in different positions and on various body types. The physical and virtual garment fit have been objectively assessed by calculating the vacant space between the garment and the body [22]. Comparing subjective feedback obtained from physical trials to the ease and strain values obtained from virtual try-on indicated that the participants reported more discomfort in areas of higher strain, however, the perception of ease was different [18].

Researchers have rigged the body scan avatars to enable movement and analyze fit in different active positions such as walking [30] and rock climbing [31]. Mixamo, an online auto-rigging service has been frequently used to generate animations from structures such as bones and joints based on marker positioning [32]. Several software programs such as Clo3D, and Browzwear VStitcher provide the ability to simulate garments on the rigged avatars and can be used to test the interaction between the body and the garment in different positions. Creating custom simulated garments involves the following steps: (1) importing the body scanned avatar, (2) feeding the fabric properties, (3) developing the pattern pieces, (4) virtually stitching the pattern pieces, and (5) placing the pattern pieces on the avatar and simulate [33]. Analyzing garment fit in different positions allows for analysis of functional comfort in actual wear conditions [29] and exposes areas that undergo stress during movement [31]. However, there is still a need to conduct research on evaluating fit when using animated models. Therefore, the objectives of the present study were two-fold: (1) to create realistic digital simulations of the selected coverall, and (2) to compare the ease amounts taken from the digital coveralls as an initial attempt to see the differences across different poses.

3. Methods

Upon receiving an Institutional Review Board (IRB) approval, 35 male and female participants were 3D body-scanned by a Human Solutions Vitus XXL 3D full body scanner in tight-fitting tops and shorts as well as in a selected disposable coverall design. Coverall sizes were assigned based on the participants' heights and weights. Because coveralls are unisex garments and expected to fit most, both women and men were recruited. During scanning, participants did not wear shoes. Three poses, i.e., reaching front, stepping up, and A-pose (Fig.1) were chosen for 3D body scanning. When scanning, coveralls were taped at the wrists and ankles to imitate agricultural workers' efforts to stop pesticides from entering through the sleeve and leg openings [14]. Because the purpose of the present study was to analyze digital coveralls, we only used minimally clothed scans of the participants in the following steps.
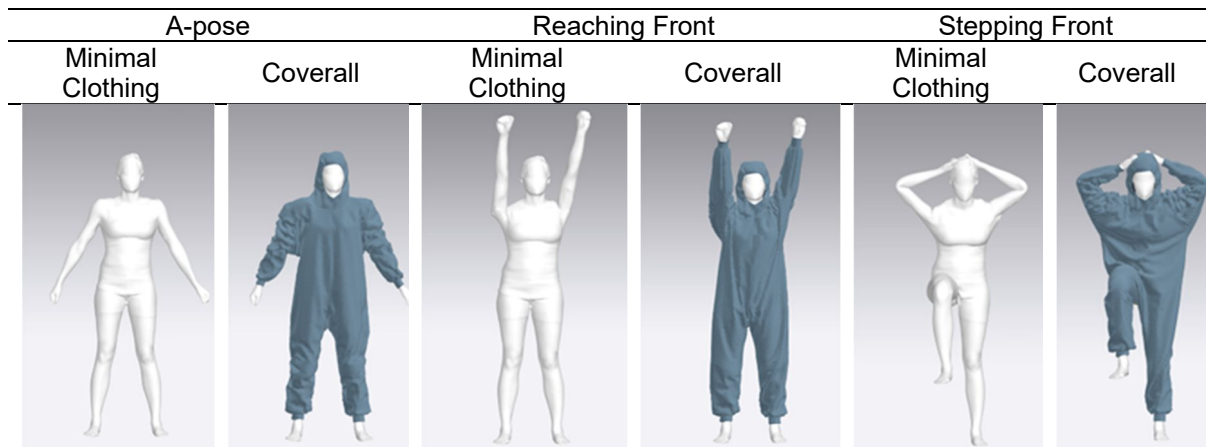
A-pose		Reaching Front		Stepping Front	
Minimal Clothing	Coverall	Minimal Clothing	Coverall	Minimal Clothing	Coverall

Fig. 1. Screenshots of a rigged body scan as it performs in the coverall and minimal clothing

The selected coverall design had pleated sections at the front knees, front and back buttocks, and underarm gussets, and was found to provide a slimmer fit and better mobility as compared to commercially available coverall designs [34]. The patterns of the coverall were digitized and graded to five sizes using Optitex PDS. Clo3D was used to virtually stitch and simulate coveralls on the rigged body scan avatars and to test the interaction between the animated body and the garment in different repetitive movements. The bodies were structured in the T-pose using Mixamo by adding bones and joints based on marker position. The rigged avatars were saved as FBX files and opened in Clo3D for further analysis. The arrangement points in Clo3D were adjusted for each 3D scan and the three poses were created and saved. Animations moved from the A-pose to the reaching front pose, and then to the stepping up pose in a looped sequence. When stitching virtual coveralls in Clo3D, the research team worked meticulously on replicating the functional pleats and imitating the taping effect at the wrist and ankles. The pinning method in Clo3D was used to make the sleeve and pants stay in the right position when the arms and legs were raised (Fig.2).
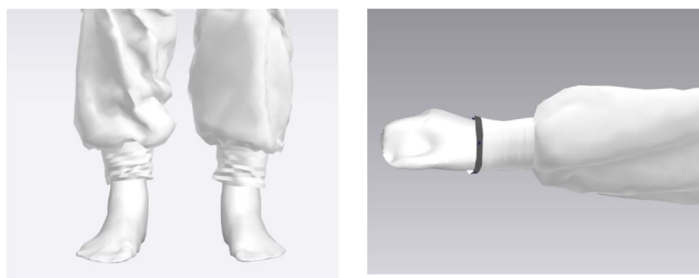

Fig.2 Virtual coverall after pinning at the ankles and wrists to replicate taping

The Fabric Assurance by Simple Testing (FAST) system was used to measure the nonwoven fabric weight, bending rigidity, and thickness values. Fabric drape was also compared to the images in Clo3D's fabric drape library to make the closest match. Additionally, the avatars with and without coveralls were exported as obj files into GeoMagic Wrap for fit analysis. The fit of the PPC was analyzed through a two-pronged approach, (1) objectively by taking cross-sections and volume measurements from both minimally clothed scans as well as scans with virtually simulated coveralls, and (2) subjectively by conducting visual fit analysis.

For the minimal scan/ body as well as the A-pose, volumes, crotch heights, cross sections, and circumferences at the bust, waist, and hip levels were measured. For the reaching pose, volume, crotch height, cross sections, and circumferences at the hip were measured. For the stepping front pose, all the measurements except the cross-section at the hip were calculated. Extracting the hip cross section was difficult as well as unreliable as the area included the entire thigh of the person. Because the study objectives were to analyze and compare ease amounts (areal and circumferential) at the selected locations, as well as the overall ease amount around the body (i.e., volume), and to see how crotch ease changed during movements, body measurements were subtracted from the coverall measurements. Findings were compared across the three poses and analyzed in SPSS 21 by performing one-way ANOVA with post hoc multiple comparisons using Tukey HSD.

To evaluate fit subjectively, front as well as back views, cross-sections at the bust, waist, and hip levels, and the ease distributions around the torso at the sagittal plane were compared. Additionally, animated models were closely examined to better understand the digital coverall-digital body relationship. Analyzing garment fit in these positions exposed the areas that would undergo stress during movement. When evaluating the animated models, how volume moved as poses changed and the locations of the restrictions or excess fabric were taken as clues to inform about comfort and function.

4. Results and Discussion

Of the 29 useable digital files of the participants, 21 (72%) were women and eight (28%) were men. Participants' ages ranged from 19 to 41 years, with a mean of 23 years. The mean height of participants was 169.00 centimeters, and the mean weight was 63.92 kilograms. The ethnic distribution of the participants was as follows: 16 (55.17%) European American, eight (27.59%) Asian/ Asian American, three (10.34%) Hispanic, and two (6.90%) African/ African American. In terms of weight status (Body Mass Index), most of the participants (n=25, 86%) were in the healthy weight group, three of the participants (10%) were overweight, and 4% of the remaining participants were underweight. FAST

results revealed the following nonwoven fabric properties: fabric weight=60.26 g/m², bending rigidity (B)= 23.23 µN.mm, thickness= 0.0245 mm.

4.1. Objective fit analysis

Descriptive statistics from the measurements were presented in Table 1. One-way ANOVA revealed that there was a statistically significant difference in mean volumes between body and coverall between at least two groups (F = (3, 84) = 5.76, p<.05). Tukey's HSD Test for multiple comparisons found that the mean value of volume difference was significantly different for the reaching front (M= 29,120.0, SD= 6,779.84, p=.016) and stepping front (M= 28,695.25, SD= 8,369.26, p=.009) poses when compared to the A-pose (M= 34,812.9, SD= 7,769.35). A-pose yielded the highest volume, or overall ease, measurement, followed by reaching front and stepping front.   There was no statistically significant difference between the reaching front and stepping front groups (p= .98).

Regarding how the vertical ease provided by the coverall at the crotch level changed, there was a statistically significant difference among the three poses as determined by one-way ANOVA (F = (3, 75) = 6.93, p<.05). A Tukey HSD post hoc test revealed that the mean value of crotch ease was significantly different between A-pose (M= 6.16, SD= 6.42) and stepping front (M= 1.99, SD= 1.29, p = .01). as well as stepping front and reaching front (M= 7.89, SD= 14.93, p = .00). There was no statistically significant difference between the reaching front and A-pose groups (p = .78). Crotch ease was the lowest in the stepping front pose, due to the raised leg. Ease was the highest in the relaxed pose, that is A-pose. Unlike the expectations, raising arms did not create a significant displacement in the coverall crotch position for the digital coveralls.

The means of the cross-sectional ease at the hip level were significantly different between the A-pose (M= 268.34, SD= 73.57) and the reaching front pose (M= 195.06, SD= 165.80), (F = (1, 56) = 4.73, p<.05). Hip cross-sectional area difference became smaller in the reaching front pose, which is plausible because when the coverall is pulled upward by the arm movement the sides would get closer to the body. When the circumferences at the hip level were compared, A-pose's outline was shorter than the reaching front's outline, however, this difference was not statistically significant (p=.08).

Table 1. Volume, area, and circumference measurement differences (coverall-body) in three poses.

		A-pose			Reaching Front			Stepping front		
		N	Mean	SD	N	Mean	SD	N	Mean	SD
	Volume (cm³)	29	34,812.9	7,769.35	29	29,120.0	6,779.84	29	28,695.25	8,369.26
Cross section	Bust (cm²)	27	263.50	116.71	29	N/A	N/A	29	321.89	240.90
	Waist (cm²)	29	391.13	51.24	29	N/A	N/A	29	372.67	152.21
	Hip (cm²)	29	268.34	73.57	29	195.06	165.80	N/A	N/A	N/A
Circumference	Bust (cm)	29	52.55	18.26	N/A	N/A	N/A	29	51.33	32.10
	Waist (cm)	29	45.66	9.57	N/A	N/A	N/A	29	54.19	29.49
	Hip (cm)	29	25.75	10.05	29	36.5	5.69	N/A	N/A	N/A
	Crotch ease (cm)	28	6.16	6.42	28	7.89	14.93	22	1.99	1.29

4.2. Subjective fit analysis

4.2.1. Static models

Cross sections at the bust, waist, and hip levels were visually analyzed in Geomagic Wrap for the same size coverall in three different planes for both female and male participants in the A-pose (Fig.3) and one female participant across the three poses (Fig.4). For the A-pose, there was plenty of ease at the selected cross sections for the participants who wore the same digital coverall size (L). However, participants' differences in body shapes and proportions affected how the ease was distributed in the selected areas. Analyzing the horizontal as well as vertical cross sections side by side gave a good understanding of the ease profiles.
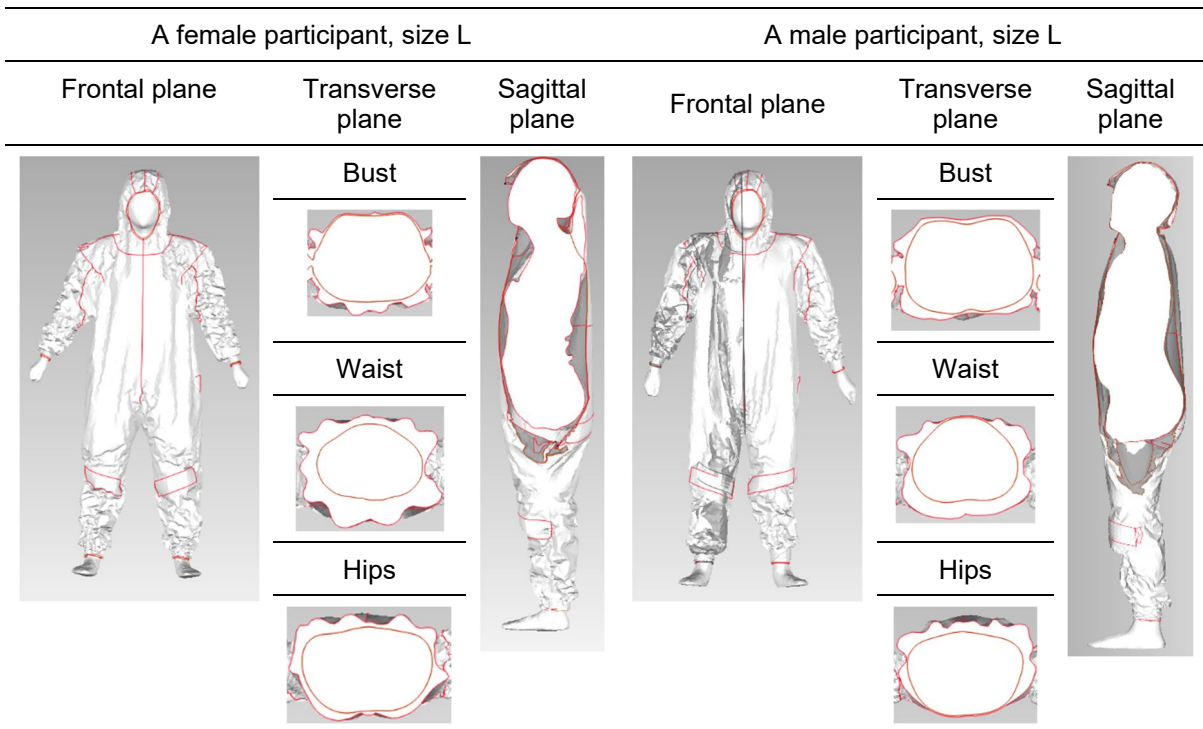
A female participant, size L			A male participant, size L		
Frontal plane	Transverse plane	Sagittal plane	Frontal plane	Transverse plane	Sagittal plane
	Bust			Bust	
	Waist			Waist	
	Hips			Hips	

Fig.3. Frontal, transverse, and sagittal plane views for a female and a male participant, in size L, A- pose.

As can be seen in Fig.4, how ease was distributed for each pose varied based on how the body moved. For the reaching front pose, ease was accumulated in the front of the body as the arm positions were pulling the digital garment forward. For stepping front, the area became more elliptical as compared to the areas in the A-pose, where coverall folds were relatively more evenly distributed around the body.
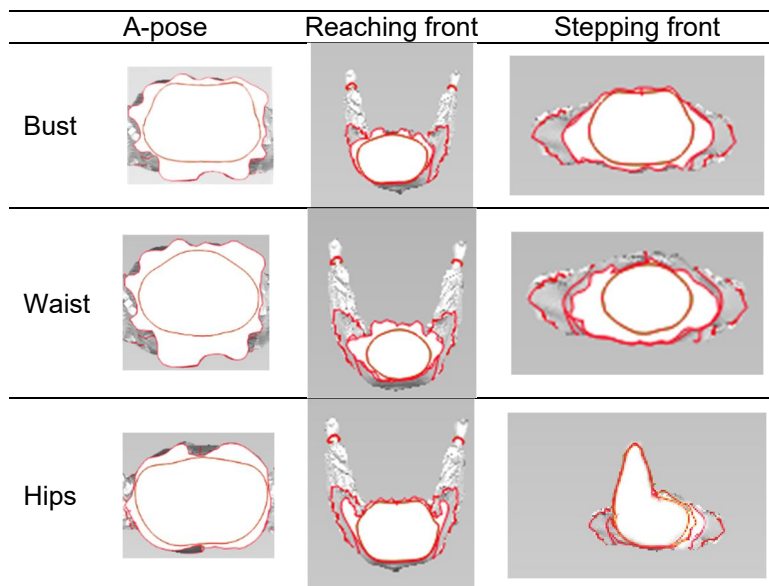
	A-pose	Reaching front	Stepping front
Bust			
Waist			
Hips			

*Fig.4. Cross sections at the bust, waist, and hip levels to visualize ease distributions
for three poses for a size M female participant*

4.2.2. Animated models

Digitally pinning the coverall at the wrist and ankle allowed the coverall to resist stretching itself, thus making the diagonal tight wrinkles visible on a digital coverall (Fig. 5). Observation of the animated models provided helpful insights to better explain the movement of the coverall and show the areas under stress as the bodies move. In the A-pose, there were no pulls or draglines, which indicated that there was no tightness. Instead, there was excess fabric materializing as folds at the extremities, such

as below the knee and the elbow. The crotch of the coverall was frequently lower than the body crotch. The pleated panels at the knee, hip, and underarm remained closed.

As the models moved from the A-pose to the reaching front pose, the arms of the wearer were raised which caused the pleats in the armhole panel to extend as well as the entire coverall to lift up. Draglines originated from the front and back crotch, radiating towards the underarm. Since the bodies were hard objects in the simulation, coverall fabric often got stuck between the thighs, especially, for XL-size wearers. Contrary to the objective analysis findings, which indicated no significant difference in crotch ease between the reaching front and A-pose groups, draglines originating from the crotch in the reaching front pose were clearly visible. This finding is an indicator of why objective analysis should be accompanied by subjective analysis.

During a real try-on, the human body is a soft object, which allows the fabric to move up to the crotch level despite the thighs of the wearer being close to each other. However, in the present study, the researchers had to manually move the legs of the model further apart to ensure that the digital fabric was released from between the thighs and raised to the crotch. The pleated panels at the knee and hip remained closed during the pose transition, and there were folds at the lower leg indicating excess fabric.

When the models moved back from the reaching front pose to the A-pose, the draglines disappeared, the pleats at the armhole panel closed and the excess fabric collected at the extremities of the legs and arms. In the next stage, the model moved from the A pose to the stepping front pose, which changed the distribution of excess fabric. When the leg of the model was raised, the crotch of the garment moved up to match the crotch of the body, and the excess fabric collected above the crotch level. The pleated panel at the knee and hip opened when the leg was raised to 90 degrees and prevented any draglines from originating. As the arms of the wearer raised from the sides to behind the head, a few drag lines originated from the center front at waist level to the underarm panel indicating a lack of fabric. The excess fabric from the lower arm moved to the upper arm.
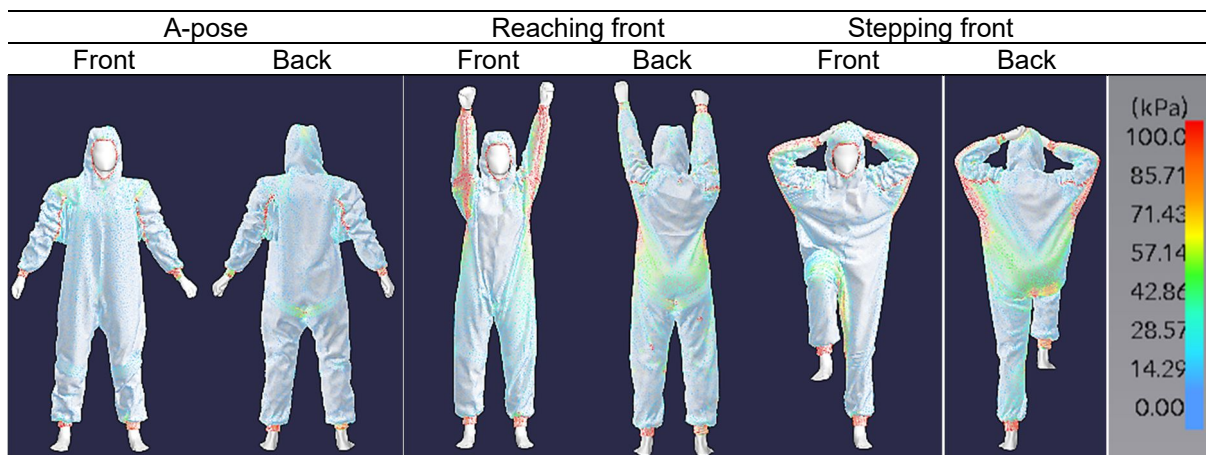
A-pose		Reaching front		Stepping front	
Front	Back	Front	Back	Front	Back

Fig.5. Pressure maps used to further examine tighter/ looser areas during animations

5. Conclusion

Simulations have been heavily used in the apparel industry for product development and can be useful tools when evaluating garment performances. Working with digital models can save costs and time, especially if we can use existing body scan databases. Although both static and animated simulations are still in the improvement phase, it is a promising technology due to its low cost [35] as compared to 4D scanners that can capture bodies in motion. Moreover, with the simulations, it is possible to avoid 3D body scanners' limitations, such as the fact that some active poses may not be captured without holes/ missing data in the scan. Animation files can improve our understanding of the body-garment relationship.

The novel procedure applied for fit analysis in the present study provided an opportunity to analyze the fit of garments in different poses, evaluate the interaction between the body and garment as well as assess the movement of ease during body movement by using a single A-pose body scan. Using virtual coveralls not only helped eliminate the tedious process of superimposing minimally clothed and clothed bodies but also increased the accuracy of alignment.

Our study findings from the objective measurements showed that measurements taken from the digital coveralls detected significant differences across the three different poses. When the rigged body scans moved, ease amounts shifted, and their profiles changed. On the digital coveralls, we were able to see where the seams or panels were located on the garments in Geomagic Wrap, which further helped evaluate the alignment of the coverall on body landmarks. We also observed how garment ease was moving and how this affected the virtual fit. The steady movement from one pose to another in addition to the ability to pause, rotate, and zoom proved to be an effective tool when evaluating the animations for movement of ease as well as the development of draglines and folds with body movement. Such movement is difficult to replicate in real-world situations. At the same time, the study reinforced the fact that only objective or only subjective analyses do not provide an accurate representation of garment fit.

Using hard body avatars was one of the biggest drawbacks in the fit analysis process. The interaction between the hard body scan avatars and the soft human body is often different, which was especially noted in the interaction between the garment and the body in the crotch area. For the present study, we used only one software program, Clo3D, to create the digital coveralls. A future study should consider using an additional 2D/3D CAD patternmaking program. As a follow-up study, we will compare our findings to the measurements from the actual body scans to analyze the reliability of our findings.

Acknowledgment

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